A compressor protection method and system capable of continuously establishing compressor discharge temperature set points based on actual in-service conditions and detecting damaged compressor valves for a given cylinder at each stage of compression. The method and system utilize sensors configured to monitor process property parameters (e.g., temperature and pressure) at the inlet section and outlet section of a compressor stage. The sensors generate monitored signals corresponding to the process property parameters. The method and system utilize a controller configured to receive and process these monitored signals. The controller executes a control logic that uses the monitored signals to either estimate or calculate compressor valve pressure losses for determining internal cylinder pressures, which are used to calculate compressor discharge temperature set points. The control logic compares the monitored temperature to the temperature set points and may generate a warning or normal operation signals based on results of the comparison.
FIGURE 2

201 COLLECT PROCESS PROPERTY PARAMETERS

202 DETERMINE PRESSURE LOSS

203 CALCULATE TEMPERATURE SET POINTS

204 COMPARE FIRST OUTLET TEMPERATURE SET POINT TO OUTLET TEMPERATURE

205 $T_{\text{OUTLET}} \geq T_{\text{SPI}}$

- NO: GENERATE NORMAL OPERATION SIGNAL
- YES: 206

206

207 GENERATE FIRST WARNING SIGNAL

208 DISPLAY FIRST WARNING

209 COMPARE SECOND OUTLET TEMPERATURE SET POINT TO OUTLET TEMPERATURE

210 $T_{\text{OUTLET}} \geq T_{\text{SP2}}$

- NO
- YES: GENERATE SECOND WARNING SIGNAL

211 GENERATE SECOND WARNING SIGNAL

212 DISPLAY SECOND WARNING

213 INITIATE COMPRESSOR SHUTDOWN
FIGURE 3

301. COLLECT PROCESS PROPERTY PARAMETERS

302. DETERMINE PRESSURE LOSS

303. CALCULATE TEMPERATURE SET POINTS

304. COMPARE FIRST OUTLET TEMPERATURE SET POINT TO OUTLET TEMPERATURE

305. $T_{OUTLET} \leq T_{SP}$

306. NO

307. GENERATE NORMAL OPERATION SIGNAL

308. YES

309. GENERATE FIRST WARNING SIGNAL

310. DISPLAY FIRST WARNING

311. INITIATE COMPRESSOR SHUTDOWN
FIGURE 4

CALC. DISCHARGE TEMP = 251 °F
SHUTDOWN TEMP = 275.61 °F
ACTUAL DISCHARGE TEMP = 259 °F

FIGURE 5

MONITORED DISCHARGE TEMP = 161 °F
MONITORED SUCTION TEMP = 60 °F
MONITORED SUCTION PRESS = 200 PSIG

FIGURE 6

RATIO OF SPECIFIC HEATS

1.400
COMPRESSOR DISCHARGE TEMPERATURE MONITOR AND ALARM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/482,952 filed on May 5, 2011, which is hereby incorporated by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

THE NAMES OF THE PARTIES TO A JOINT RESEARCH AGREEMENT

[0003] Not applicable.

INCORPORATION-BY-REFERENCE OF MATERIAL SUBMITTED ON A COMPACT DISC

[0004] Not applicable.

BACKGROUND OF THE INVENTION

[0005] 1. Field of the Invention
[0006] The present disclosure relates to subject matter for pumping fluids, in particular reciprocating compressors having a separate sensor that is responsive to the occurrence of a condition or a change in condition of either the compressor or the gas being compressed.

[0007] 2. Description of Related Art
[0008] Reciprocating compressors are often utilized to increase the pressure of a gas by displacing a positive volume of gas by alternatively filling and discharging a cylinder by the movement of a piston, plunger or diaphragm. Reciprocating compressors may be either single-stage or multi-stage, and the cylinders may either be fitted with single or double acting pistons.

[0009] Within an individual stage, there may be one or more compressor cylinders. In the case of a stage with multiple cylinders, the cylinders may be arranged in parallel. The cylinders may be lubricated or non-lubricated and have an inlet (suction) valve and an outlet (discharge) valve. Failure of these valves can have significant consequences, including the loss of rod force reversals during each stroke. The loss of rod force reversals will prevent adequate lubrication to the load bearing components, which include the crankshaft main bearing, the connecting rod bearing, and the compressor crosshead pin. The loss of adequate lubrication at these components will often result in extensive compressor damage and/or failure (e.g. premature bearing wear or failure, and so forth) leading to forced outages, loss of production, safety risks to workers, inefficient operation, unnecessary maintenance work and high repair costs. Therefore, it is of critical importance to detect valve failure and prevent any potential damage.

[0010] One direct indicator of valve damage or failure is increased compressor discharge temperature. As a result, several protection systems have been developed to detect compressor valve failure by monitoring compressor discharge temperature. One such system utilizes an operator determined fixed temperature set point that automatically activates an alarm or shuts down the compressor upon detecting a discharge temperature that exceeds the set point.

[0011] However, systems with a fixed operator determined constant temperature set point are often inadequate to address the reality of actual in-service conditions. In particular, compressor discharge temperature generally does not remain constant over time. Rather, it is typically variable and dependent upon other conditions including gas composition, suction pressure and temperature, and discharge pressure. For example, if a fixed compressor discharge temperature set point has been established based on a suction temperature of 70° F. and the suction temperature decreases (or increases) due to a change in local conditions (e.g. ambient temperature, suction pressure, and so forth), then the set point may be too high (or too low). In the case of a fixed set point that is too low, this may result in a false alarm leading to costly and unnecessary shutdowns and lost production time. Alternatively, in the case of a set point that is too high, this may result in compressor valve failure or damage going unnoticed. Thus, a protection system with a fixed operator determined temperature set point discharge temperature that does not continuously update based on changing service conditions may be inadequate to protect a compressor.

[0012] Another type of compressor protection system is a continuous analyzer system that utilizes a plurality of sensors positioned to monitor the internal conditions of each cylinder. These sensors monitor the temperatures and pressures of the gas inside each cylinder and the vibrations at each cylinder. Such a system is often effective in detecting compressor valve damage. However, this type of system also has disadvantages. Significantly, this type of continuous analyzer system can be extremely costly because it typically requires special pressure sensors installed to measure internal cylinder pressures and adapted for severe pulsation and a very fast response time. In addition, this system has high operating costs because of the severe pulsation within a compressor cylinder, which causes the load sensing diaphragm of the special pressure sensor to experience metal fatigue causing intermittent failures, which require high cost replacement sensors. Further, theoretical discharge temperatures calculated with this system are often inaccurate, particularly for high-speed compressors, because the system uses terminal pressure to calculate theoretical discharge temperature. That is, this system measures the internal cylinder pressure at the top and bottom of each piston stroke when the piston is stopped and at the point of reversing directions. As a result, the terminal pressure is usually equal to suction and discharge external flange pressure and is not adjusted to account for true internal cylinder minimum and maximum pressures.

[0013] Accordingly, there remains a need in the art for a more practical, cost effective, and improved compressor protection method and system that is capable of continuously establishing variable compressor discharge temperature set points based on actual in-service conditions and detecting damaged compressor valves for a given cylinder at each stage of compression.

BRIEF SUMMARY OF THE INVENTION

[0014] An object of this invention is to provide a more practical and cost effective compressor protection method and system capable of continuously establishing variable compressor discharge temperature set points based on actual in-service conditions. A further object of this invention is to provide a compressor protection method and system capable of detecting damaged compressor valves for a given cylinder at each stage of compression. Still a further object of this
invention is to accurately calculate theoretical discharge temperature for a compressor. Additional objects and advantages of this invention shall become apparent in the ensuing descriptions of the invention.

[0015] Accordingly, a more practical, cost effective and improved compressor protection method and system that is capable of continuously establishing compressor discharge temperature set points based on actual in-service conditions and detecting damaged compressor valves for a given cylinder at each stage of compression. The method and system utilize sensors configured to monitor process property parameters at the inlet section and outlet section of a compressor stage. The monitored process property parameters include temperature and pressure. The sensors generate monitored signals corresponding to the process property parameters. The method and system also utilizes a controller configured to receive and process these monitored signals. The controller executes a control logic that uses the monitored signals to either estimate or calculate compressor valve pressure losses for determining internal cylinder pressures, which are used to calculate compressor discharge temperature set points. The control logic compares the monitored temperature to the temperature set points and may generate a warning or normal operation signals based on results of the comparison.

[0016] The foregoing brief summary of the invention presents a simplified summary of the claimed subject matter in order to provide a basic understanding of some aspects of the claimed subject matter. This summary is not an extensive overview of the claimed subject matter. It is intended to neither identify key or critical elements of the claimed subject matter nor delineate the scope of the claimed subject matter. Its sole purpose is to present some concepts of the claimed subject matter in a simplified form as a prelude to the more detailed description that is presented below.

[0017] Additionally, the foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be understood. Additional features and advantages of the invention will be described hereinafter, which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiments disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims. The novel features, which are believed to be characteristic of the invention, both as to its organization and method of operation, together with further objects and advantages will be better understood from the following description when considered in connection with the accompanying figures. It is to be expressly understood, however, that each of the figures is provided for the purpose of illustration and description only and is not intended as a definition of the limits of the present invention.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

[0018] The accompanying drawings illustrate preferred embodiments of this invention. However, it is to be understood that these embodiments are not intended to be exhaustive, nor limiting of the invention. These embodiments are but examples of some of the forms in which the invention may be practiced.

[0019] FIG. 1 illustrates a process and instrument diagram for an embodiment of a compressor protection system in accordance with this invention used with a multi-stage reciprocating compressor.

[0020] FIG. 2 illustrates a block diagram of a compressor protection method having a first warning signal and a second warning signal in accordance with this invention.

[0021] FIG. 3 illustrates a block diagram of a compressor protection method having a first warning signal in accordance with this invention.

[0022] FIGS. 4, 5, and 6 illustrate examples of simplified displays that may be shown on a display device in accordance with this invention.

DETAILED DESCRIPTION OF THE INVENTION

[0023] The claimed subject matter is now described with reference to the drawings, wherein like reference numerals are used to refer to like elements throughout. FIG. 1 illustrates an embodiment of a compressor protection system in accordance with this invention used with a multi-stage reciprocating compressor. Although the subsequent discussion is in reference to a multi-stage reciprocating compressor, the compressor protection system may also be used with any compressor that increases the pressure of a gas by alternatively filling and discharging a cylinder, including a single-stage reciprocating compressor.

[0024] As shown generally at 100, a multi-stage reciprocating compressor comprises a first compression stage (110) and second compression stage (120) with each stage having at least one cylinder. The cylinders are configured to increase the pressure of a gas by the movement of a piston, plunger or diaphragm in the cylinder. Each compression stage (110, 120) has an inlet or suction section (111, 121) configured to receive a gas and an outlet or discharge (112, 122) section configured to discharge the gas. The inlet section comprises inlet piping and an inlet compressor valve, and the outlet section comprises outlet piping and an outlet compressor valve.

[0025] The reciprocating compressor may also comprise a knock-out vessel (113, 123, 133) configured to separate the liquid and gas phases of a fluid. The knock-out vessels (113, 123, 133) are preferably located at least upstream of the compression stages (110, 120) and/or downstream of any heat-exchangers to ensure most entrained liquids are substantially separated from the fluid prior to it entering the compression stage (110, 120). Each knock-out vessel (113, 123, 133) typically has an inlet to receive a gas, a liquid outlet, and a vapor outlet. The knock-out vessel (113, 123, 133) may also include a mist eliminator, such as a mesh pad or baffles, configured to minimize the entrainment of any liquid droplets in the gas. The knock-out vessel may be sized and oriented (e.g. horizontal, vertical) in any manner that substantially removes liquid from the gas. Suitable design guidelines for knock-out vessels are well-known in the art, e.g. A. Kayode Coker, Ernest E. Ludwig (2007). Ludwig’s Applied Process Design for Chemical and Petrochemical Plants (Volume 1, 4th edition), Burlington: Gulf Professional Publishing.

[0026] The reciprocating compressor may further comprise a heat exchanger (114, 124), such as an intercooler, configured to receive a gas and remove the heat of compression from the gas. The heat exchanger (114, 124) is preferably located following the outlet of the compression stage (110, 120). As
the fluid passes through the heat exchanger (114, 124), it is cooled and the gas phase may partially or fully condense to a liquid. As discussed above, in order to prevent possible equipment damage, it is preferable to route the gas from the heat exchanger to a knock-out vessel to substantially remove any liquids before sending the gas to the compression stage. Suitable design guidelines for heat exchangers are well-known in the art, e.g., A. Kayode Coker, Ernest E. Ludwig (2007). Ludwig’s Applied Process Design for Chemical and Petrochemical Plants (Volume 1, 4th edition). Burlington: Gulf Professional Publishing.

[0027] The compressor protection system comprises a plurality of sensors (115, 116, 117, 118, 125, 126, 127, 128). The sensors are configured to monitor selected process property parameters at the inlet section (111, 121) and outlet section (112, 122) of a compression stage and generate a plurality of monitored signals corresponding to the selected process property parameters. The selected process property parameters correspond to actual in-service operating conditions. The sensors may be new or existing, which include sensors that are part of an existing control or monitoring system.

[0028] The selected process property parameters include those required for calculation methods, which are well-known in the art, that sufficiently approximate pressure losses and compressor discharge temperature. For example, pressure losses associated with gas flowing through compressor valves (and other valves), pipe and fittings may be calculated using derivations of the Bernoulli theorem as detailed in several publications known in the art such as Crane Co. (2009, September). Flow of Fluids Through Valves, Fittings and Pipe (Technical Paper No. 410). Stamford, Conn. Compressor valve pressure losses may also be sufficiently approximated using data obtained by observation during periodic compressor performance testing by instruments with internal pressure sensors (e.g., internal pressure sensors available from Windrock and Beta Corporation, compressor manufacturer performance calculation method(s) (e.g. Ariel Corporation. (2001). Application Manual Ariel Calculation Method. Mount Vernon, Ohio.), or compressor manufacturer performance program(s) (e.g. Ariel Corporation Performance Program all versions).

[0029] Examples of selected process property parameters that may be monitored to calculate pressure losses include, but are not limited to, pressure, temperature, piston diameter, valve area(s), piston speed, gas flow rate, gas composition, k value (the ratio of specific heats (Cp/Cv)), gas specific gravity, viscosity, molecular weight, and so forth. As one of ordinary skill in the art appreciates, the gas specific gravity and k value may be determined by use of data tables from reference manuals (e.g. Perry’s Chemical Engineer’s Handbook which is hereby incorporated by reference in its entirety (Don W. Perry, Robert H. Perry (2008). Perry’s Chemical Engineer’s Handbook (8th edition), McGraw-Hill.), or by use of computer programs or simulators known to those of ordinary skill in the art (e.g. use of the Ariel Performance Program by input of a representative or actual gas analysis will yield both the k value and the gas specific gravity).

[0030] Process property parameters that may be monitored to calculate compressor discharge temperature include those required for calculation methods using the adiabatic gas compression temperature calculation method, which is well-known in the art. The adiabatic gas compression gas compression temperature may be calculated by the following equation:

\[ T_{\text{ad}} = T_s \times \left( \frac{P_1}{P_s} \right)^{\frac{k-1}{k}} \]

where \( T_{\text{ad}} \) is calculated compressor discharge temperature (degrees Rankine), \( T_s \) is the monitored compressor suction temperature (degrees Rankine), \( P_1 \) is calculated or estimated outlet internal compressor cylinder pressure (psia), \( P_s \) is calculated or estimated inlet internal compressor cylinder pressure (psia), and \( k \) is the ratio of specific heats or k value of the compressed gas (dimensionless). Other calculation methods similar to the adiabatic gas compression calculation methods may also be used. For example, the polytropic gas compression formula, which is well-known in the art, may also be used to calculate compressor discharge temperature.

[0031] Examples of selected parameters that may be monitored to calculate compressor discharge temperature include, but are not limited to, gas pressure, gas temperature, compressor speed, gas composition, gas specific gravity, and so forth. Some of these process property parameters may also be derived from other process property parameters using other calculation methods, computer simulation packages, or gas property tables.

[0032] As shown in FIG. 1, the compressor protection system comprises a plurality of sensors configured to monitor gas temperature (116, 118, 126, 128) and gas pressure (115, 117, 125, 127) located at the inlet (111, 121) and outlet (112, 122) of each compression stage. The temperature and pressure sensors generate signals corresponding to the monitored temperatures and pressures. The temperature (116, 118, 126, 128) and pressure sensors (115, 117, 125, 127) may be located at any location that provides a representative and sufficiently accurate measurement of the temperature and pressure at or near the inlet (or outlet) of each compressor cylinder within a stage. Locating the sensors in these locations eliminates the requirement for special sensors to measure internal cylinder pressures. The temperature and pressure sensors should also be compatible with the gas and design conditions of the reciprocating compressor system.

[0033] In an embodiment, the compressor protection system has at least one inlet temperature sensor (116, 126) and at least one inlet pressure sensor (115, 125) located at or near the inlet of each compression stage. Additional inlet temperature and pressure sensors may be provided in order to provide redundant measurements to verify measurements and so forth if desired. The sensors (115, 116, 125, 126) are preferably located as close as practical to the inlet of the compressor cylinder; however, as discussed above, these sensors (115, 116, 125, 126) may be located at any location that provides a representative and sufficiently accurate measurement of the temperature and pressure at or near the inlet of each compressor cylinder within a stage. Examples of suitable sensor locations include, but are not limited to, a suction vessel such as a pulsation vessel, knock-out vessel, and so forth.

[0034] The compressor protection system also has at least one outlet pressure sensor (115, 125) located at or near the outlet of the compression stage. Additional outlet pressure sensors may be provided in order to provide redundant measurements to verify measurements and so forth if desired. The outlet pressure sensor is preferably located as close as practical to the outlet of the compressor cylinder; however, as discussed above, these sensors (115, 116, 125, 126) may be located at any location that provides a representative and
sufficiently accurate measurement of the temperature and pressure at or near the outlet of each compressor cylinder within a stage. Examples of suitable sensor locations include, but are not limited to, a suction vessel such as a pulsation vessel, knock-out vessel, and so forth.

[0035] The compressor protection system also includes at least one outlet temperature sensor (118, 128) for each cylinder within the compressor stage. Additional outlet temperature sensors (118, 128) may be provided in order to provide redundant measurements to verify measurements and so forth if desired. Sensors are provided at or near the outlet of each cylinder in order to discriminate which cylinder may be experiencing valve failure. The outlet temperature sensor (118, 128) should be located as close as practical to the outlet of each compressor cylinder within a compressor stage, e.g., between the compressor cylinder and the compressor discharge nozzle, to ensure a sufficiently accurate representative measurement of the discharge temperature of the gas. The compressor discharge nozzle is typically directly attached to the compressor cylinders. The outlet temperature sensor (118, 128) may also be located at other locations provided that care is taken to obtain a representative discharge temperature of the gas from the compressor cylinder. In addition, outlet temperatures sensor may be added at the location of each compressor outlet valve, typically through the valve retaining mechanical devices, to discriminate individual gas temperatures at each valve, and thereby detect individual outlet valve failures.

[0036] The compressor protection system further comprises a controller (140). The controller (140) is capable of receiving the monitored selected process property parameter, and performing the required calculations on a continuously updating basis. Such a controller would typically be a programmed microprocessor configured to receive and process the monitored signals transmitted from the plurality of sensors via electrical connections (e.g. electrical wires, data transmission cables, etc.) or by wireless signals transmitted over a wireless network. The signals may be direct analog signals or digital communication signals. The controller (140) is also configured to execute control logic for performing various analyses including calculating operating set points, comparing the set points with the monitored signals, generating alarm signals, and so forth. The controller (140) may be integrated into a new or existing control system, including additional programming of a programmable logic controller (PLC) system, or human machine interface (HMI) with sufficient excess processing capability, or other means. Examples of suitable controllers include, but are not limited to, Altronic DE series control systems, Murphy Millennium and Centurion systems, Allen Bradley PLC systems, Red Lion, and so forth.

[0037] The compressor protection system may also include a computing device or display device (150) configured to receive signals such as warning signals, monitored selected process property parameter signals, set points, alarms, and so forth. The display device (150) may also be configured to display the warning signals as well as other information such as monitored compressor speed and selected process property parameters from the sensors, calculated variables, and so forth. FIGS. 4, 5, and 6 illustrate examples of simplified displays (400, 500, 600) that may be shown on a display device in accordance with this invention.

[0038] Turning now to FIG. 2, in operation, the compressor protection system utilizes a controller configured to execute a control logic comprising a process property parameter collection component, an internal cylinder pressure calculation component, a temperature set point calculation and comparison component, and a signal component.

[0039] The process property parameter collection component comprises using the sensors to collect selected process property parameters (201) and generate a plurality of monitored signals corresponding to the collected property parameters. The sensors are configured to continuously collect data and transmit signals to the controller. The time period over which the sensors collect selected property parameter data and transmit corresponding signals typically depends on the compressor system. The sensors may collect data and transmit signals over a time period of less than one second. However, the compression protection system and method may be just as effective over a longer period of time, e.g. fifteen minutes.

[0040] In a preferred embodiment, the sensors collect gas temperature and pressure data at the inlet and outlet of each compression stage. Sensors may also be provided to collect compressor speed data and/or atmospheric pressure data. The sensors then generate signals corresponding to the collected data and transmit the signals to the controller. In addition to the temperature and pressure data, the ratio of specific heats of the gas entering each compression stage should also be determined. The ratio of specific heats may be a fixed input into the controller as a constant value based on known data from actual or representative gas analysis of the gas entering the compressor used in conjunction with known calculation methods, computer simulation packages, or gas property tables. Alternatively, the ratio of specific heats may also be continuously updated using data transmitted from a sensor configured to measure required properties to determine the ratio of specific heats. The sensor may include an output signal, either in digital or analog form that may be used as a continuous input value for calculations in the compressor protection system. An example of a suitable sensor configured to determine the ratio of specific heats include, but are not limited to, a continuous gas analyzer available by and from Dynalco, Windrock, Beta, Hoerbiger, and so forth.

[0041] The internal cylinder pressure calculation component comprises determining the pressure loss associated with the flow of the gas through the compressor cylinder inlet valve(s) and outlet valve(s) (202). The internal cylinder pressure calculation component determines the pressure loss by either estimating or calculating the pressure loss using monitored selected process property parameter data and deriving a theoretical internal compressor cylinder inlet pressure and outlet pressure. The resultant internal compressor inlet pressure and outlet pressure are then used to calculate a predicted compressor discharge temperature. The resultant internal compressor inlet pressure and outlet pressure may also be adjusted in proportion to the compressor speed.

[0042] The internal compressor cylinder pressures may be determined using the following equations:

\[ P_d = P_i P_{inlet} \]

\[ P_{inlet} = P_{outlet} P_{inlet} \]

where \( P_i \) is inlet or suction internal compressor cylinder pressure (psia), \( P_d \) is pressure monitored by the inlet pressure sensor (psia), \( P_{inlet} \) is inlet compressor valve pressure loss (psia), and \( P_{outlet} \) is outlet or discharge internal compressor cylinder pressure
(psia), \( P_c \) is pressure monitored by the outlet pressure sensor (psia), and \( P_{\text{vac}} \) is outlet compressor valve pressure loss (psia).

Compressor valve pressure loss may be determined by either using fixed condition estimates with adjustments for variable speed where necessary or continuously calculated. Fixed condition estimates of pressure loss may be determined using multiple sources. Example sources include, but are not limited to, data obtained by observation during periodic compressor performance testing by instruments with internal pressure sensors (e.g. internal pressure sensors available from Windrock, or Beta Corporation, or Bentley-Nevada part #165855), compressor manufacturer's performance calculation method or performance program (e.g. Ariel Corporation Performance Program all versions, Ariel Corporation Calculation Method), and derivations of the Bernoulli theorem as detailed in several publications known in the art such as Crane Co. (2009, September). Flow of Fluids Through Valves, Fittings and Pipe (Technical Paper No. 410). Stamford, Conn.

The fixed condition estimates of pressure loss should be at the rated speed of the compressor. In cases where the compressor system operates at variable speeds, the fixed condition pressure loss should be updated continuously by methods described below. The fixed condition pressure loss may be adjusted by linear reduction of the fixed condition pressure loss in direct proportion of the actual compressor speed to the rated compressor speed. Alternatively, the fixed condition pressure loss may also be adjusted by exponential reduction of the pressure loss estimate in proportion to the actual compressor speed relative to the rated compressor speed, e.g. pressure loss is typically directly proportional to the square of the compressor speed.

Determining pressure losses based on fixed condition estimates is preferably used in cases where the compressor inlet pressure and outlet pressure conditions are substantially fixed. Substantially fixed conditions are generally required for the estimates of valve pressure losses to be sufficiently accurate for the intended purpose. It is preferred that compressor stage inlet and outlet pressures are within about +/-20% of those associated with the valve pressure loss estimates for the fixed conditions. Further, the fixed condition estimates of valve pressure losses are expected to be sufficiently accurate where the compressed gas specific gravity varies from the fixed condition reference specific gravity by about +/-8%. For compressed gases with a variable specific gravity, continuously calculated methods should be used. Examples of gases with a variable specific gravity include, but are not limited to, field gas gathering operations, mixed gas streams in gas processing operations, gas blending operations, or other operations which vary the gas composition of different specific gravities.

As discussed above, valve pressure losses may also be continuously calculated using sensors configured to monitor selected process property parameters necessary to calculate pressure loss. Continuous calculations of valve pressure losses may be determined using data obtained either by observation during periodic compressor performance testing with instruments with internal pressure sensors, or compressor manufacturer's performance calculation method or performance program (e.g. Ariel Corporation Performance Program all versions, Ariel Corporation Calculation Method). The data should be obtained over the anticipated range of operation of the compressor system. The data may also be made available for continuous calculations using a lookup table. Continuous calculations of valve pressure losses may also be determined using derivations of the Bernoulli theorem as detailed in several publications known in the art such as Crane Co. (2009, September). Flow of Fluids Through Valves, Fittings and Pipe (Technical Paper No. 410). Stamford, Conn.

In addition to adjusting the monitored pressures for compressor valve pressure loss, the internal cylinder pressure calculation component may also calculate a pressure loss associated with the gas flow between the inlet pressure sensor and inlet compressor valve as well as the pressure loss between the outlet pressure sensor and outlet compressor valve. These pressure losses may account for pressure loss associated with gas flow through any pipe, fittings, equipment, or other valves that may be between the pressure sensor and the compressor valve. When accounting for pressure loss associated with both compressor valves, pipe fittings, and other valves, the internal compressor cylinder pressures may be determined using the following equations:

\[
P_f = P_i - P_{\text{vac}} - P_{\text{rline}}
\]

\[
P_f = P_i - P_{\text{vac}} + P_{\text{rline}}
\]

where \( P_{\text{rline}} \) is the pressure loss of gas flowing through pipe, fittings, and other valves between the inlet pressure sensor and inlet compressor valve pressure loss (psia), and \( P_{\text{rline}} \) is the pressure loss of gas flowing through pipe, fittings, and other valves between the outlet pressure sensor and outlet compressor valve pressure loss (psia). Pressure loss associated with gas flow through pipes, fittings, and other valves may be determined using estimates from compressor manufacturers or calculated using derivations of the Bernoulli theorem as discussed above.

The temperature set point calculation and comparison component comprises using the calculated internal compressor cylinder pressures and collected process property parameter data to calculate the calculated compressor discharge temperature \((T_{\text{d}})\) using the equation discussed above. The temperature set points for equipment shutdown protection should be calculated based on the calculated discharge temperature and adjusted by a fixed value and/or a percentage value, and continuously compared to the actual compressor discharge temperature. In addition, operator notification by an alarm is desirable. Such alarm discharge temperature set point values may be calculated based on the calculated discharge temperatures and adjusted by a fixed value and/or a percentage value and continuously compared to the actual compressor discharge temperature. The percentage and fixed values to accomplish the alarm and shutdown protection are more fully described below.

The temperature set point calculation and comparison component calculates a first and second temperature set point \((203)\) for the compressor outlet (discharge) temperature for a given compression stage. The first temperature set point may be calculated using the following equation:

\[
T_{\text{spt1}} = T_{\text{d}} \times C_1
\]

where \( T_{\text{spt1}} \) is the first temperature set point (degrees Rankine), \( T_{\text{d}} \) is calculated compressor discharge temperature (degrees Rankine), and \( C_1 \) is a first constant (dimensionless). The value of the first constant is selected based on the amount that the monitored compressor discharge temperature \((T_{\text{d}})\) may exceed the calculated compressor discharge temperature \((T_{\text{d}})\) before generating a first warning signal. For example, if it is desired that the monitored compressor discharge tem-
perature only exceed the calculated compressor discharge temperature by 12% before generating a first warning signal, then the first constant has a value of 1.12. As one of ordinary skill in the art appreciates, the value used for $C_1$ may be selected by the end user as desired and/or on an application basis.

[0050] The first temperature set point may also be calculated using the following equation:

$$T_{SP1} = T_{de} + C_2$$

where $T_{SP1}$ is the first temperature set point (degrees Rankine), $T_{de}$ is calculated compressor discharge temperature (degrees Rankine), and $C_2$ is a second constant (dimensionless).

As with the first constant, the value of the second constant is selected based on the amount that the monitored compressor discharge temperature ($T_d$) may exceed the calculated compressor discharge temperature ($T_{de}$) before generating a first warning signal. However, instead of a fixed percentage, the second constant is a fixed value. For example, if it is desired that the monitored compressor discharge temperature only exceed the calculated compressor discharge temperature by 15 degrees before generating a first warning signal, then the first constant has a value of 1.15. As one of ordinary skill in the art appreciates, the value used for $C_2$ may be selected by the end user as desired and/or on an application basis.

[0051] The second temperature set point may be calculated using the following equation:

$$T_{SP2} = T_{de} + C_3$$

where $T_{SP2}$ is the second temperature set point (degrees Rankine), $T_{de}$ is calculated compressor discharge temperature (degrees Rankine), and $C_3$ is a third constant (dimensionless). The value of the third constant is selected based on the amount that the monitored compressor discharge temperature ($T_d$) may exceed the calculated compressor discharge temperature ($T_{de}$) before generating a second warning signal. For example, if it is desired that the monitored compressor discharge temperature only exceed the calculated compressor discharge temperature by 22% before generating the second warning signal, then the third constant has a value of 1.22. As one of ordinary skill in the art appreciates, the value used for $C_3$ may be selected by the end user as desired and/or on an application basis.

[0052] The temperature set point calculation and comparison component further comprises comparing the first temperature set point to the monitored compressor discharge temperature ($T_d$) to determine if the two values are consistent or inconsistent with one another. The signal component uses results of the temperature set point calculation and comparison component to generate signals such as a normal operation signal, a warning signal, and so forth. If the monitored compressor discharge temperature is less than the first temperature set point ($T_{SP1}$), then the controller generates a normal operation signal ($S_{normal}$) and returns to the initial step of collecting selected process property parameters ($P_{collection}$). However, if the monitored compressor discharge temperature is greater than or equal to the first temperature set point ($T_{SP1}$), then the controller generates a first warning signal ($S_{warning}$). The controller may execute a control logic that sends the first warning signal to a computer device or display device ($D_1$) so that it may be displayed to an operator. The aforementioned signal generation and display steps may occur simultaneously.

[0053] If the controller generates the first warning signal, the controller has control logic that then compares the second temperature set point to the monitored compressor discharge temperature ($T_{SP2}$). If the monitored compressor discharge temperature is less than the second temperature set point ($T_{SP2}$), then the controller returns to the initial step of collecting selected process property parameters ($P_{collection}$). However, if the monitored compressor discharge temperature is greater than or equal to the second temperature set point ($T_{SP2}$), then the controller generates a second warning signal ($S_{warning2}$). The controller may execute a control logic that sends the second warning signal to a computer device or display device ($D_2$) so that it may be displayed to an operator. The controller may also execute a control logic that initiates compressor shutdown ($S_{shutdown}$) upon generation of the second warning signal to prevent damage to compressor valves for a given cylinder. The compressor may be shut down by the controller or an existing control system switching off the power or fuel source to the compressor. The aforementioned signal generation, display steps and shutdown steps may occur simultaneously.

[0054] As shown in FIG. 3, in an alternate embodiment the compressor protection system may initiate a compressor shutdown upon generation of a first warning signal. The compressor protection system utilizes a controller having control logic configured to execute a process property parameter collection component. The process property parameter collection component uses the one or more sensors to collect selected process property parameters ($P_{collection}$) and generate a plurality of monitored signals corresponding to the selected process property parameters. The control logic further comprises and internal cylinder pressure calculation component configured to determine the pressure loss associated with the gas flowing between the inlet and outlet pressure sensors ($S_{internal pressure}$). The control logic also comprises a temperature set point calculation and comparison component that uses the results from the internal cylinder pressure component to calculate the calculated compressor discharge temperature ($T_{de}$) and a first temperature set point ($T_{SP1}$). The control logic for aforementioned steps ($P_{collection}$, $S_{internal pressure}$, $S_{shutdown}$) operates in the same manner as steps discussed above ($P_{collection}$, $S_{warning}$, $S_{warning2}$) for the embodiment of FIG. 2 except that the control logic does not calculate a second temperature set point.

[0055] The temperature set point calculation and comparison component then compares the first temperature set point to the monitored compressor discharge temperature ($T_d$) to determine if the two values are consistent or inconsistent with
one another. A signal component uses these comparison results to generate signals. If the monitored compressor discharge temperature is less than the first temperature set point (305), then the controller generates a normal operation signal (306) and returns to the initial step of collecting selected process property parameters (301). However, if the monitored compressor discharge temperature is greater than or equal to the first temperature set point (305), then the controller generates a first warning signal (307). The controller may execute a control logic that shows the first warning signal on a computer device or display device (308) and initiates compressor shutdown (309) to prevent damage to compressor valves for a given cylinder. The compressor may be shut down by the controller or an existing control system switching off the power or fuel source to the compressor. The aforementioned signal generation, display steps and shutdown steps may occur simultaneously.

[0056] The present invention described in detail above provides significant advantages over the prior art. In particular, the present invention is a more versatile, cost effective, and improved compressor protection method and system that is capable of continuously establishing variable compressor discharge temperature set points based on actual in-service conditions and detecting damaged compressor valves for a given cylinder at each stage of compression. Further, instead of requiring a plurality of sensors installed in each cylinder at its inlet and outlet as well as vibration sensors at each cylinder, the present invention may operate with temperature and pressure sensors installed only at the inlet and outlet of each compression stage.

[0057] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the art will appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

What is claimed is:

1. A method for protecting a compressor with at least one compression stage having at least one cylinder, an inlet section configured to receive a gas wherein the inlet section comprises inlet piping and an inlet compressor valve, an outlet section configured to discharge the gas wherein the outlet section comprises outlet piping and an outlet compressor valve, sensors configured to monitor selected process property parameters at the inlet section and outlet section and generate monitored signals corresponding to the process property parameters, and a controller configured to receive the monitored signals, execute a control logic and generate signals, the control logic comprising:

   a. a process property parameter collection component comprising:
      i. collecting data for the monitored selected process property parameters at the inlet section and outlet section using the sensors, wherein the monitored process property parameters comprise gas inlet temperature, gas inlet pressure, gas outlet temperature, gas outlet pressure, and compressor speed;
   b. an internal cylinder pressure calculation component comprising:
      i. determining an inlet internal cylinder pressure;
      ii. determining an outlet internal cylinder pressure;
   c. a temperature set point calculation and comparison component comprising:
      i. calculating a first outlet temperature set point for each cylinder;
      ii. comparing the first outlet temperature set point with the monitored gas outlet temperature for each cylinder;
   d. a signal component comprising:
      i. generating a normal operation signal if the monitored outlet temperature is consistent with the first outlet temperature set point.
      ii. generating a first warning signal if the monitored outlet temperature is inconsistent with the first outlet temperature set point.

2. A method for protecting a compressor according to claim 1 wherein:
   a. the inlet internal cylinder pressure is determined by calculating a first pressure loss for the inlet compressor valve;
   b. the outlet internal cylinder pressure is determined by calculating a second pressure loss for the outlet compressor valve.

3. A method for protecting a compressor according to claim 1 wherein:
   a. the inlet internal cylinder pressure is determined by estimating a first pressure loss for the inlet compressor valve;
   b. the outlet internal cylinder pressure is determined by estimating a second pressure loss for the outlet compressor valve.

4. A method for protecting a compressor according to claim 1 wherein the first pressure loss and second pressure loss are adjusted in proportion to the compressor speed.

5. A method for protecting a compressor according to claim 1 wherein the signal component further comprises:
   a. initiating compressor shutdown if the monitored outlet temperature is inconsistent with the first outlet temperature operating range.

6. A method for protecting a compressor according to claim 5 wherein the temperature set point calculation and comparison component further comprises:
   a. calculating a second outlet temperature set point for each cylinder;
   b. comparing the second outlet temperature set point with the monitored outlet temperature for each cylinder.

7. A method for protecting a compressor according to claim 1 wherein the signal component further comprises:
   a. generating a second warning signal if the monitored outlet temperature is inconsistent with the second outlet temperature set point;
   b. initiating compressor shutdown if the outlet temperature is inconsistent with the second outlet temperature operating range.
8. A method for protecting a compressor according to claim 7 wherein the process property parameter collection component further comprises:
   a. collecting data using a sensor configured to measure required properties to determine the ratio of specific heats.
9. A method for protecting a compressor according to claim 8 wherein the pressure losses are calculated using fixed operating conditions.
10. A method for protecting a compressor according to claim 8 wherein the pressure losses are continuously calculated using actual operating conditions.
11. A protection system for a compressor with at least one compression stage having at least one cylinder, an inlet section configured to receive a gas and an outlet section configured to discharge the gas, wherein the inlet section comprises inlet piping and an inlet compressor valve and the outlet section comprises outlet piping and an outlet compressor valve, wherein the protection system comprises:
   a. a plurality of sensors configured to monitor selected process property parameters at the inlet section and outlet section and generate a plurality of monitored signal corresponding to the selected process property parameters;
   b. a controller configured to execute a control logic, wherein the control logic comprises:
      i. a process property parameter collection component;
      ii. an internal cylinder pressure calculation component;
      iii. a temperature set point calculation and comparison component;
      iv. a signal component.
12. A protection system for a compressor according to claim 11 wherein
   a. the process property parameter collection component comprises:
      i. collecting data for the monitored process property parameters at the inlet section and outlet section using the sensors, wherein the monitored process property parameters comprise gas inlet temperature, gas inlet pressure, gas outlet temperature for each cylinder, gas outlet pressure, and compressor speed;
   b. the internal cylinder pressure calculation component comprises:
      i. determining an inlet internal cylinder pressure;
      ii. determining an outlet internal cylinder pressure.
13. A protection system for a compressor according to claim 12 wherein:
   a. the inlet internal cylinder pressure is determined by calculating a first pressure loss for the inlet compressor valve;
   b. the outlet internal cylinder pressure is determined by calculating a second pressure loss for the outlet compressor valve.
14. A protection system for a compressor according to claim 12 wherein:
   a. the inlet internal cylinder pressure is determined by estimating a first pressure loss for the inlet compressor valve;
   b. the outlet internal cylinder pressure is determined by estimating a second pressure loss for the outlet compressor valve.
15. A protection system for a compressor according to claim 13 wherein the first pressure loss and second pressure loss are adjusted in proportion to the compressor speed.
16. A protection system for a compressor according to claim 15 wherein the temperature set point calculation and comparison component comprises:
   a. calculating a first outlet temperature set point;
   b. comparing the first outlet temperature set point with the monitored outlet temperature.
17. A protection system for a compressor according to claim 16 wherein the signal component further comprises:
   a. generating a normal operation signal if the monitored outlet temperature is consistent with the first outlet temperature set point;
   b. generating a first warning signal if the monitored outlet temperature is inconsistent with the first outlet temperature set point.
18. A protection system for a compressor according to claim 17 wherein the signal component further comprises:
   a. initiating compressor shutdown if the monitored outlet temperature is inconsistent with the first outlet temperature operating range.
19. A protection system for a compressor according to claim 18 wherein the temperature set point calculation and comparison component further comprises:
   a. calculating a second outlet temperature set point for each cylinder;
   b. comparing the second outlet temperature set point with the monitored outlet temperature for each cylinder.
20. A protection system for a compressor according to claim 19 wherein the signal component further comprises:
   a. generating a second warning signal if the monitored outlet temperature is inconsistent with the second outlet temperature set point;
   b. initiating compressor shutdown if the outlet temperature is inconsistent with the second outlet temperature operating range.
21. A protection system for a compressor according to claim 20 wherein the process property parameter collection component further comprises:
   a. collecting data using a sensor configured to measure required properties to determine the ratio of specific heats.
22. A protection system for a compressor according to claim 21 wherein the pressure losses are calculated using fixed operating conditions.
23. A protection system for a compressor according to claim 21 wherein the pressure losses are continuously calculated using actual operating conditions.

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